The cold formation and decay of superheavy nuclei including the orientation degree of freedom

R.K. Gupta[1], M. Balasubramaniam[1], R. Kumar[1], N. Singh[1]

[1] Panjab University, India

gupta_rajk@hotmail.com

Theoretically, cold synthesis of new and superheavy elements (SHE) was proposed by one of us and collaborators [1-3] as back as in 1974-75, where a method was given for selecting out an *optimum* cold target-projectile combination. Cold compound systems were considered to be formed for *all* those target + projectile combinations that lie at the bottom of the *potential energy minima*, referred to as "cold reaction valleys" or reaction partners leading to "cold fusion" [2-6]. This information on cold reaction valleys was optimized [3] by the requirements of smallest interaction barrier, largest interaction radius and non-necked (no saddle) nuclear shapes, identifying the cases of "cold", "warm/ tepid" and "hot" fusion reactions. The theory, called the Quantum Mechanical Fragmentation Theory (QMFT), was advanced as a unified approach both for fission (including the cluster radioactivity (CR)) and heavy ion collisions. The key result behind the cold fusion reaction valleys (or the decay products in fission and CR) is the *shell closure effects* of one or both the reaction partners (or decay products). Also, fission and CR were considered as cold phenomenon on the basis of the QMFT, prior to their being observed experimentally as cold processes in 1980 and 1984, respectively [7].

In this paper, we review this theory via some new calculations based on the use of oriented and radioactive nuclei as beams and/ or targets. The use of neutron-rich radioactive nuclei is essential for overshooting the *center* of island of SHE (the next doubly magic nucleus) and the deformed oriented collisions could be useful since the fusion barrier gets lowered, or, in other words, the excitation energy of the cold compound system gets further reduced. As an example, we choose the recently used highly neutron-rich beam of ^{48}Ca on neutron-rich actinide targets ^{232}Th, ^{238}U, ^{242,244}Pu and ^{248}Cm, forming the compound systems $^{280}110^*$, $^{286}112^*$, $^{290,292}114^*$ and $^{296}116^*$ [8]. Note that the targets used are the deformed nuclei and, for near the Coulomb barrier energies, the compound nucleus excitation energy $E^* \sim 30$-35 MeV, in between the one for cold (10-20 MeV) and hot (40-50 MeV) fusion reactions. The resulting "warm/ tepid" compound systems de-excite by 3n and/ or 4n evaporations (and γ rays), compared to 1n and 2n in cold and 5n in hot fusion reactions, and give rise to new nuclei $^{277}110$, $^{283}112$, $^{287,288,289}114$ and $^{292}116$. These final nuclei are relatively long-lived and decay only via α-particles, giving the α-genetically related nuclei, called an α-decay chain. Then, as a second aim of this paper, we investigate the observed α–decay characteristics of these nuclei within the preformed cluster decay model (PCM) of Gupta and Collaborators [9-11] which is also based on the QMFT.

The QMFT is a dynamical theory of the three cold processes mentioned above, worked out in terms of the mass (charge) asymmetry $\eta=(A_1-A_2)/(A_1+A_2)$ ($\eta_Z=(Z_1-Z_2)/(Z_1+Z_2)$), the relative separation **R**, the deformations β_1^{λ}, β_2^{λ} (λ=2) of two nuclei or, in general, the fragments, and the neck parameter ε [12,13]. We extend the QMFT here to include the multipole deformation parameter λ=3 and 4 i.e. octupole and hexadecupole deformations also. In addition, we introduce two orientation angles θ_1 and θ_2 [14], see Fig. 1(a). So far, the time-dependent Schrödinger equation in η is solved for non-oriented collisions and for weakly coupled η and η_Z motions:

$$H\Psi(\eta,t)=i\hbar\frac{\partial}{\partial t}\Psi(\eta,t). \qquad (1)$$

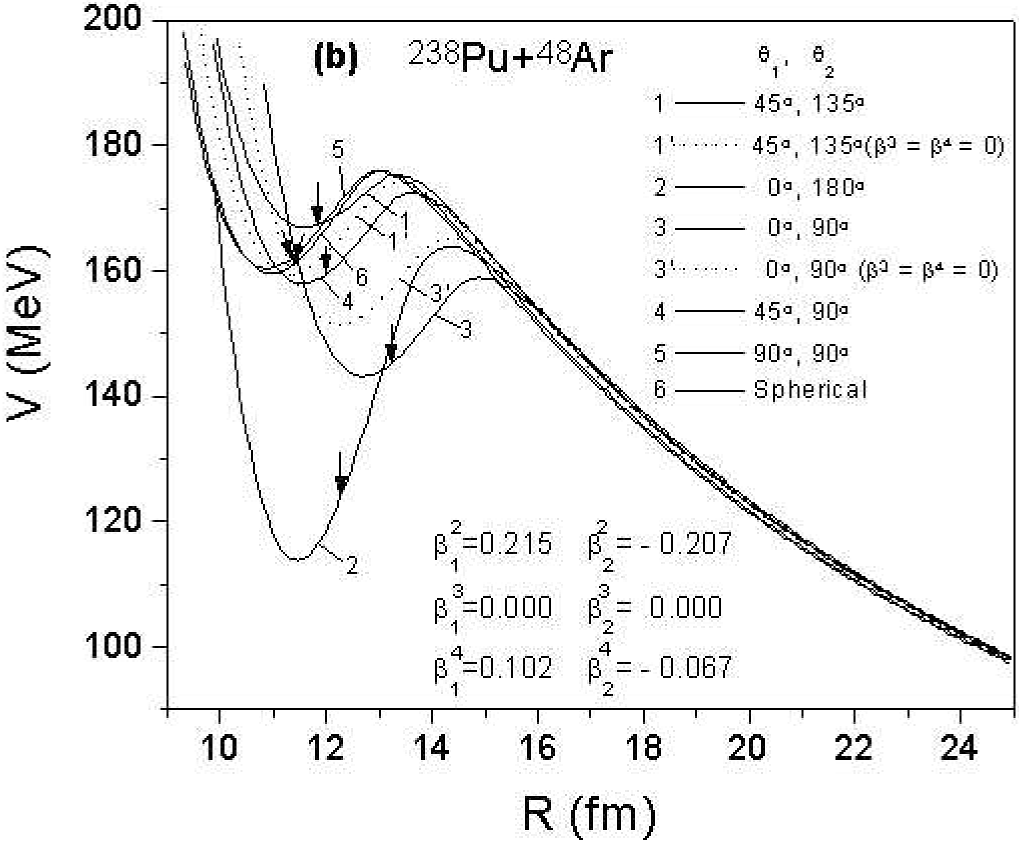

Figure 1. (a) Schematic configuration of two axially symmetric quadrupole deformed, oriented nuclei, in same plane. (b) Scattering potentials for $^{48}Ar+^{238}Pu$ at different orientations. Arrows denote R-values for s_0=1.0 fm.

Here R(t) is treated classically and the quadrupole deformations β_i^2 (i=1,2) and ε are fixed by minimizing the collective potential $V(R,\eta,\eta_Z, \beta_i^2,\varepsilon)$ in the above coordinates. Eq. (1) is solved for a number of heavy systems [13], which shows that for target + projectile combinations coming from *outside* the potential energy minima, a few nucleon to a large mass transfer occurs, whereas the same is zero for a target + projectile referring to potential energy minima. This means that *for cold reaction partners, the two nuclei stick together and form a deformed compound system*. A few nucleon transfer may, however, occur depending on whether a "conditional" saddle exists or not. Since the solution of Eq. (1) is very much computer-time consuming, the following simplifications are exercised based on calculated quantities.

The potentials $V(R,\eta)$ and $V(R,\eta_Z)$, calculated within the Strutinsky method i.e. $V=V_{LDM} + \delta U$, the liquid drop energy plus the shell effects calculated by using the asymmetric two-center shell model (ATCSM), show that the motions in both η and η_Z are much faster than the R-motion. This means that these both potentials are nearly independent of the R-coordinate and hence R can be taken as a time-independent parameter. This reduces the time-dependent Schrödinger equation (1) in η to the stationary Schrödinger equation in η,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}+V_R(\eta)\right\}\Psi_R^{(\nu)}(\eta)=E_R^{(\nu)}\Psi_R^{(\nu)}(\eta) \tag{2}$$

where R is fixed at the post saddle point. This choice of R-value is justified by many good fits to both fission and heavy-ion collision data [7] and by an explicit, analytical solution of time-dependent Schrödinger equation in η_Z coordinate [15]. An interesting result of these calculations is that the yields ($\propto |\Psi(\eta)|^2$ or $|\Psi(\eta_Z)|^2$, respectively, for mass or charge distributions) are nearly insensitive to the detailed structure of the kinetic energy term in the Hamiltonian i.e. the Cranking masses $B_{\eta\eta}$ calculated consistently by using ATCSM. In other words, the static potential $V(\eta)$ or $V(\eta_Z)$ contain all the important information of a fissioning or colliding system. The positions of the minima are due to shell effects. Since these potentials are nearly independent of the choice of R-value, we have calculated them at some critical distance R_c where the two nuclei come in close contact with each other. We do the same here for oriented, neutron-rich radioactive nuclei having higher multipole deformations also.

For oriented nuclei, the potential $V(\eta)$ is the sum of binding energies (taken from Möller et al. [16] for $Z\geq8$; and from experiments for $Z\leq7$), the Coulomb and the proximity potential (both taken from [14] and extended to include higher multipole deformations) that depend on deformations as well as on orientations:

$$V(\eta)=\sum_{i=1}^{2}B\left(A_i,Z_i,\beta_i^{\lambda}\right)+E_c(Z_i,\beta_i^{\lambda},\theta_i)+V_P(A_i,\beta_i^{\lambda},\theta_i). \tag{3}$$

In Eq. (3) i=1,2 and λ =2,3,4. For the fixed orientations, the charges Z_1 and Z_2 in (3) are fixed by minimizing this potential in η_Z coordinate (which fixes the deformation coordinates β_i^{λ}). The relative separation distance R, in terms of the minimum surface separation distance s_0, is $R=s_0+R_1(\alpha_1)\cos\psi_1+R_2(\alpha_2)\cos\psi_2$. For a fixed R, s_0 is different for different orientations. Alternatively, for fixed s_0, R is different for different orientations, and we use this latter one in the following.

Fig. 1(b) illustrates for prolate-oblate ^{238}Pu+ ^{48}Ar reaction, the scattering potentials at different orientations (for λ=2,3,4 and λ=2 alone). An interesting result is that the barrier is lowered in each case except for 90^0-90^0 configuration, and that the barrier is lowest for 0^0-90^0 configuration. Note that for prolate-prolate collisions, the barrier is lowest for 0^0-180^0 configuration [14]. Thus, in the following, we neglect the 90^0-90^0 configuration since for fusion it is as un-favorable as the spherical nuclei. Also, note that the inclusion of higher multipole deformations is not always favored (barriers lowered) since for 45^0-135^0 and 45^0-90^0 orientations the barrier gets raised, rather than lowered as in 0^0-90^0, 0^0-180^0 and 90^0-90^0 (see Fig. 1(b) for 45^0-135^0 and 0^0-90^0 cases).

Fig. 2(a) illustrates the fragmentation potentials for various orientations of different target + projectile combinations at a fixed separation s_0=1.0 fm, forming the same compound nucleus $^{286}112^*$ (for 0^0-180^0 s_0=1.5 fm, since in this configuration the nuclei come much closer to each other). Apparently, due to the orientation degree of freedom, the energies of all the potential minima are lowered and the largest effect of the higher multipoles is for 0^0-180^0 which though is not the most favorable orientation for fusion (barrier not lowest) . We concentrate here only on the ^{48}Ca or ^{50}Ca minimum (marked by vertical lines; for some orientations, Ca changes to Ar). We notice that w.r.t. ground state energy (also marked), the Ca and/ or Ar minima have now the excitation energies E^*~15-20 MeV compared to ~ 30 MeV for spherical nuclei. This means that Ca or Ar beam could be used for cold fusion reactions, if the colliding target nuclei are oriented, a result obtained for the first time. Note that ^{50}Ca is also a radioactive nucleus and all orientations and higher multipole deformations are not always favorable for the fusion process.

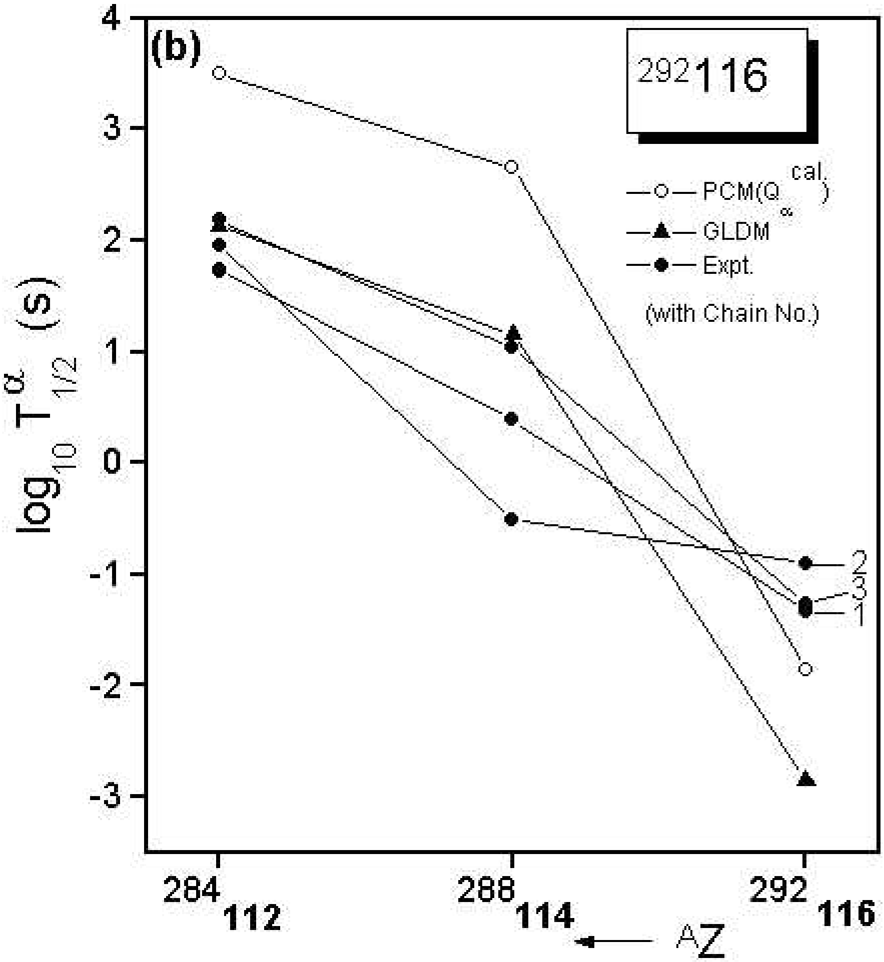

Figure 2. (a) Fragmentation potentials of $^{286}112^*$ for various orientations of different target + projectile combinations with λ=2,3,4 and λ=2 alone. For Z≤ 7, β_i^2 are from RMF with TM2 force [17]. (b) Calculated half-lives for α-decay chain of $^{292}116$, compared with experiments and GLDM calculation.

For α-decay studies, the preformed cluster-decay model (PCM) used here is also based on QMFT and hence on the same coordinates as are introduced above. In a PCM, the decay half-life is defined as,

$$T_{1/2} = \frac{\ln 2}{P_0 \nu_0 P} \tag{4}$$

The P_0, the cluster (and daughter) preformation probabilities in the ground state of nucleus referring to η-motion, are the solutions of the stationary Schrödinger equation (2) for the ground-state ν=0, and P, referring to R-motion, is WKB tunneling penetrability. The ν_0 is the barrier assault frequency. For details, see Refs. [9-11].

Fig. 2(b) illustrates our results of calculation for α-decay chain of $^{292}116$ parent [18], compared with the experimental data and another recent calculation [19], denoted GLDM. The numbers 1,2,3 in the figure mean that more than one chain is observed. We notice that the comparisons of $T_{1/2}$ values for the two models with experiments are within experimental errors, i.e. within less than two orders of magnitude. Both model calculations give similar trends.

Summarizing, we have extended the QMFT for use of oriented collisions and including higher multipole deformations, which result in the reduction of excitation energies of the compound system formed due to different target-projectile combinations. This means that both the "warm" and "hot" fusion reactions could also be reached in "cold fusion", if the target and/or projectile were oriented and have also octu- and hexa-decapole deformations. The QMFT based PCM is also shown to explain the α-decay characteristics of SHE.

References

[1] H.J. Fink, W. Greiner, R.K. Gupta, S. Liran, H.J. Maruhn, W. Scheid and O. Zohni, *Proc. Int. Conf. on Reactions between Complex Nuclei*, Nashville, Tenn., USA, 1974, North-Holland Pub. Co., Vol. 2, p. 21.

[2] A. Sândulescu, R.K. Gupta, W. Scheid and W. Greiner, Phys. Lett. B **60**, 225 (1976).

[3] R.K. Gupta, A. Sândulescu and W. Greiner, Phys. Lett. B **67**, 257 (1977).

[4] R.K. Gupta, C. Pârvulescu, A. Sândulescu and W. Greiner, Z. Physik A **283**, 217 (1977).

[5] R.K. Gupta, A. Sândulescu and W. Greiner, Z. Naturforsch. 32 **a**, 704 (1977).

[6] R.K. Gupta, Sovt. J. Part. Nucl. **8**, 289 (1977).

[7] R.K. Gupta; and R.K. Gupta et al., *Heavy Elements and Related New Phenomena* edited by W. Greiner and R.K. Gupta (World Sc. Publications, 1999) Vols. I & II

[8] Yu.Ts. Oganessian, et al., Nature **400**, 242 (1999); Phys. Rev. C **62**, 041604(R) (2000); Phys. Rev. Lett. **83**, 3154 (1999); Phys. Rev. C **63**, 011301(R) (2000); Nucl. Phys. A **682**, 108c (2001).

[9] S.S. Malik and R.K. Gupta, Phys. Rev. C **39**, 1992 (1989).

[10] S. Kumar and R.K. Gupta, Phys. Rev. C **49**, 1922 (1994).

[11] R.K. Gupta and W. Greiner, Int. J. Mod. Phys. E **3**, 335 (1994, Supp.).

[12] R.K. Gupta, et al., Phys. Rev. Lett. **35**, 353 (1975); J. Maruhn and W. Greiner, *ibid*. **32**, 548 (1974).

[13] R.K. Gupta, Phys. Rev. C **21**, 1278 (1980); S. Yamaji, et. al., J. Phys. G **3**, 1283 (1977).

[14] Malhotra and R.K. Gupta, Phys. Rev. C **31**, 1179 (1985).

[15] D.R. Saroha, R. Aroumougame and R.K. Gupta, Phys. Rev. C **27**, 2720 (1983).

[16] P. Möller, J.R. Nix, W.D. Myers and W.J. Swiatecki, At. Data Nucl. Data Tables, **59**, 185 (1995).

[17] M.S. Mehta, S.K. Patra and R.K. Gupta, Private Communication (2003).

[18] S. Kumar, M. Balasubramaniam, R.K. Gupta, G. Münzenberg and W. Scheid, J. Phys. G: **29**, 625 (2003).

[19] G. Royer and R.A. Gherghescu, Nucl. Phys. A **699** (2002) 479.